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SUPPORTING SURFACE IN NONSTATIONARY FLOW NEAR SCREEN,(U)
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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

SUPPORTING SURFACE IN NONSTATIONARY
FLOW NEAR SCREEN

by

B. N. Belousov, A. N. Lukashenko, A. N. Panchenkov

FOREIGN TECHNOLOGY DIVISION

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SUPPORTING SURFACE IN NONSTATIONARY FLOW NEAR SCREEN

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	Α	α	α	Nu	Ν	ν	
Beta	Β	β		Xi	Ξ	ξ	
Gamma	Γ	γ		Omicron	Ο	ο	
Delta	Δ	δ		Pi	Π	π	
Epsilon	Ε	ε	ϵ	Rho	Ρ	ρ	ϱ
Zeta	Ζ	ζ		Sigma	Σ	σ	ς
Eta	Η	η		Tau	Τ	τ	
Theta	Θ	θ	ϑ	Upsilon	Τ	υ	
Iota	Ι	ι		Phi	Φ	φ	ϕ
Kappa	Κ	ϰ κ	ϰ	Chi	Χ	χ	
Lambda	Λ	λ		Psi	Ψ	ψ	
Mu	Μ	μ		Omega	Ω	ω	

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

SUPPORTING SURFACE IN NONSTATIONARY FLOW NEAR SCREEN

B. N. Belousov, A. N. Lukashenko, A. N. Panchenkov

At the present time there exist a number of important studies on the theory of a supporting surface in a nonstationary flow [1, 2, 3] with different approximate methods of calculating the wing. As we know, the problem of a thin supporting surface of arbitrary length is reduced to two-dimensional integral equations for which there are no closed solutions.

One of the most important aspects is that of studying two-dimensional integral equations in one-dimensional approximations and obtaining on this basis final results for the hydroaerodynamic characteristics of a wing in a nonstationary flow.

Whereas for a wing in a stationary flow Prandtl's theory of the supporting line defines the Prandtl equation in terms of the one-dimensional approximation, for a wing in a nonstationary flow the complexity of the physical phenomenon does not provide a unified approximation method. Thus, there are a large number of approaches (up to 20, as noted by R. A. Weisplinghoff, H. Ashley, and R. A. Halfman [1]) which give different one-dimensional equations.

Developed in the works of one of the authors [6, 7, 8, 9] is a method of integral operators for the theory of a lifting surface in a nonstationary flow.

The general solution to the problem is represented in the form of three components. Two components are found from equations which correspond in form to the equations of the theory of a wing in a nonstationary flow.

Also examined in [8] is a method of constructing the Prandtl equation based on the example of a wing in an unlimited fluid flow. A significant advantage of this method is that the Prandtl equation is constructed for the parametric constant of a singular solution. This has made it possible to more deeply analyze the problem and critically examine the existing theories of Reisner [1], Kusner [2], and others.

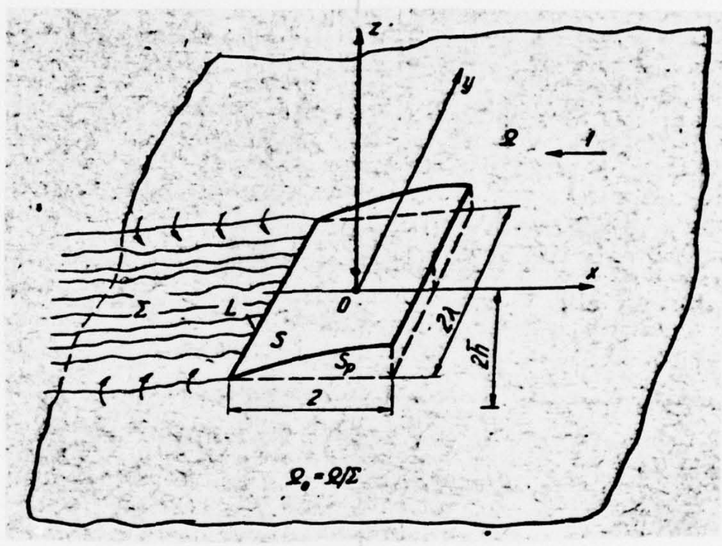
In the present article a method of integral operators is applied to the problem of a supporting surface near a screen. Obtained are two-dimensional integral equations and a one-dimensional intego-differential equation for the parametric constant. It should be mentioned that the downwash is associated only with the singular solution corresponding to a singularity in the leading edge of the wing. Transfer of this result to the theory of stationary motion indicates that the classical theory of a lifting line is strictly applicable only to a plane lifting surface.

If the lifting surface is not planar, then in the expression for the coefficient of the lifting force of the wing there appear terms on the order of $1/\lambda$ which are not considered by the classical theory. From the physical standpoint they determine the effect of aspect ratio on the angle of zero lift of the wing.

The present study adheres very closely to studies [6, 7, 8, 9], for which reason we have attempted to very briefly introduce the general results from these studies in the necessary cases and discuss new results in more detail.

1. Let us assume that a thin lifting surface S moves at velocity V_0 near a solid screen. In additional to the main forward motion it performs harmonic oscillations at frequency ω.

Assuming that the disturbances introduced into the flow by the lifting surface are small, in coordinate system oxyz moving at velocity V_0 (see the figure) let us use a known method to linearize the problem [4, 5].



In the case of harmonic oscillations for hydrodynamic potentials of velocities φ and accelerations Θ and their derivatives we have

$$\Theta^n_{x_i}(g; t) = \bar{\Theta}^n_{x_i}(g) e^{i\omega t},$$
$$\varphi^n_{x_i}(g; t) = \bar{\varphi}^n_{x_i}(g) e^{i\omega t}\, g \in \Omega_0. \tag{1.1}$$

The index n denotes the derivative of the n-order of functions Θ and φ with respect to coordinate $x_i (x_1 = x;\ x_2 = y;\ x_3 = z)$.

In equations (1.1) and henceforth we shall only study the real parts of the proper expressions, although we shall drop Re

for simplicity. Relationships (1.1) make it possible to formulate the problem for $\overline{\Theta}(g)$ and $\overline{\varphi}(g)$ and exclude time from our study.

By shifting to dimensionless space Ω, assuming that the velocity of the impinging flow equals 1 and removing the bar from the top of corresponding $\Theta(g)$ and $\varphi(g)$ expressions, we get the boundary problem in the space of the potential of the accelerations Θ:

$$\begin{aligned} &\Delta\Theta = 0; \quad g \in \Omega; \\ &\Theta_z = F(g); \quad g \in S_p; \end{aligned} \qquad (1.2)$$

(A)

$$\begin{aligned} &\Theta_z = 0; \quad z = 2\bar{h}; \\ &\Theta_+ - \Theta_- = 0, \quad g \in L; \\ &\Theta \to 0; \\ &x \to +\infty. \end{aligned} \qquad (1.3)$$

Problem (A) is obtained by integral operator $A\gamma$, assigned in space $L_1(S_p)$ with values of $C^2\Omega$. The required properties of operator $A\gamma$ are given in [5-8].

In the studied problem operator $A\gamma$ has the form of

$$A\gamma = \frac{1}{4\pi} \int_{S_p} \gamma(p) \frac{d}{d\zeta} \left[\frac{1}{r} + \operatorname{sign} F \frac{1}{r_1} \right] dS; \qquad (1.4)$$

here

$$r = \sqrt{(x-\xi)^2 + (y-\eta)^2 + (z-\zeta)^2};$$
$$r_1 = \sqrt{(x-\xi)^2 + (y-\eta)^2 + (z+\zeta+4\bar{h})^2};$$

$$\operatorname{sign} F = \begin{cases} -1 & \text{- solid screen} \\ +1 & \text{- free surface.} \end{cases}$$

According to condition (1.2) we get the two-dimensional integral equation of the problem

$$\bar{A}_z\gamma = F(g), \quad g \in S_p \qquad (1.5)$$

Let us represent the solution in the form of three components [6-8]:

$$\gamma(g) = \gamma_1(g) + \gamma_2(g) + \gamma_3(g) \qquad g \in S_p,$$

where γ_1 is the solution of class $C^1(S_p)$, related to the presence of a break in tangent velocities during transfer of the surface S_p; γ_2 - solution of class $C^1(S_p)$, which describes inertial movements; γ_3 - singular solution.

Analysis of equation (1.5) and the method of constructing equations for γ_i is given in [6].

Let us write equations for γ_1 and γ_2:

$$N_{01}\bar{A}_z\gamma_1 = F_1 + C, \quad g \in S_p; \tag{1.6}$$

$$N_{01}\bar{A}_z\gamma_2' = -ikF_1, \quad g \in S_p. \tag{1.7}$$

Here $F_1 = -\frac{d}{dx} F_2(g)$; $F_2(g)$ - the function which describes the shape of the surface S; $N_{01} = -\int^{x} d\tau$.

Constant C is found from the condition of solvability of equation (1.6) in the space of $C^1(S_p)$ [6].

By performing calculations for $N_{01}\bar{A}_z\gamma$ we get [10]

$$N_{01}\bar{A}_z\gamma = \frac{1}{2\pi}\int_{-1}^{+1}\int_{-1}^{+1} \bar{\gamma}(p)\left\{\frac{1}{dy}\frac{1}{(y-\eta)}\Big(\frac{\sqrt{(x-\xi)^2+\lambda^2(\eta)(y-\eta)^2}}{(x-\xi)} - \right.$$
$$\left. - \operatorname{sing} F \frac{(x-\xi)[(y-\eta)^2\lambda^2(\eta)(\vec{r}_1^{\,2} - \lambda^2(\eta)\,16\bar{h}^2(\eta)] - \lambda^2(\eta)\,16\bar{h}^2(\eta)\cdot(\vec{r}_1^{\,2} + \lambda^2(\eta)\,16\bar{h}^2(\eta))]}{\vec{r}_1^{\,2}}\right\} dS. \tag{1.8}$$

where

$$\bar{\gamma}(p) = \frac{\gamma(p)}{2\lambda(\eta)}.$$

The singular solution is determined from equation

$$N\bar{A}_z\gamma = F_1(g); \quad h \in S_p;$$
$$N = -e^{ikx}\int_{\infty}^{x} e^{-ik\tau}d\tau, \tag{1.9}$$

k is the Strouhal chord number.

Equation (1.9) is obtained by mapping equation (1.5) in the space of the velocity potential.

2. Now let us examine the Prandtl equation for a wing and a nonstationary flow. For a wing of great aspect ratio operator $N_{01}\bar{A}_z\gamma$ is approximated by operator

$$N_{01}\bar{A}_z\gamma = \frac{\lambda(y)}{\pi}\int_{-1}^{+1}\bar{\gamma}(\xi;\ y)\left[\frac{1}{(x-\xi)} + \operatorname{sign} F\frac{(x-\xi)}{(x-\xi)^2+16\bar{h}^2(y)}\right]dy. \tag{2.1}$$

For a plane flow the form of the singular solution γ_3 is known, and for a wing of great aspect ratio we use γ_3 in the form of the solution of the planar problem, although with a constant which depends on the y-coordinate:

$$\gamma_3 = a(y)\sqrt{\frac{1+S}{1-S}}.$$

If

$$\gamma_{12}^0 \in C^1(S) \text{ and } \gamma_2 = -ik\int_{-1}^{x}\gamma_1 d\tau; \quad g \in S_p,$$

then we get [6]

$$N\bar{A}_z\gamma_{12}^0 = N_{01}\bar{A}_z\gamma_1; \quad g \in S_p. \tag{2.2}$$

By examining equations (1.6), (1.7), (1.9) and property (2.2), we get

$$N\bar{A}_z\gamma_3 = -C - N_1\bar{A}_z\gamma_{23}.$$

Equation (1.6) can be written in the form

$$N_0\bar{A}_z\gamma_1 = F_1 + C^1, \tag{2.3}$$
$$N_0 = -\int\limits_{\infty}^{x} d\tau.$$

When $\lambda \to \infty$ $C^1 = C$, while for greater aspect ratio we use the approximation

$$C = -\frac{1}{\pi}\int\limits_{-1}^{+1} \frac{[F_1 - (N_0 - N_{01})\bar{A}_z\gamma_1]}{\sqrt{1-x^2}}dx. \tag{2.4}$$

Then, by introducing operator p^{-1}:

$$p^{-1}N_{01}\bar{A}_z\gamma_1 = \int\limits_{-1}^{+1} \gamma_1(\xi)\,d\xi$$

and taking approximation (2.1) from (2.3), we get the Prandtl equation for the regular solution, which in form coincides with the Prandtl equation of the stationary problem [4]:

$$\Gamma_1(y) = \frac{\psi\pi}{\lambda(y)}\left\{\alpha_1 - \frac{1}{2\pi}\int\limits_{-1}^{+1} \Gamma_1'(\eta)\left[\frac{1}{y-\eta} - \frac{y-\eta}{(y-\eta)^2 + 16\bar{h}^2}\right]d\right\} \tag{2.5}$$

where

$$\Gamma_1 = \int\limits_{-1}^{+1} \gamma_1(\xi)\,d\xi.$$

Function γ_{22} is found from equation

$$N_{01}\bar{A}_z\gamma_{22}' = ikC(y). \tag{2.6}$$

Now let us introduce a number of assumptions typical for the Prandtl problem [4], [8]:

$$N_1\bar{A}_z\gamma \approx N_{10}\bar{A}_z\gamma + N_{1\lambda}\bar{A}_z\gamma;$$
$$\gamma(p) = \gamma_1(\xi)\gamma_2(y);$$
$$N_{10}\bar{A}_z\gamma = 2\gamma_2(y)\lambda(y)N_{10}\bar{\bar{A}}_z\gamma_1(\xi);$$
$$N_{1\lambda} = -e^{ikx}\int\limits_{\infty}^{\xi} e^{-ik\tau}d\tau;$$
$$N_{10}\bar{\bar{A}}_z\gamma = \frac{1}{2\pi}\left\{\int\limits_{-1}^{+1} \gamma(\xi)\left[\frac{1}{(x-\xi)} + \operatorname{sign} F\frac{(x-\xi)}{(x-\xi)^2 + 16\bar{h}^2(y)}\right]d\xi + \right.$$
$$\left. + ike^{ikx}\int\limits_{-1}^{+1} \gamma(\xi)\int\limits_{\infty}^{x} e^{-ik\tau}\left[\frac{1}{(\tau-\xi)} + \operatorname{sign} F\frac{(\tau-\xi)}{(\tau-\xi)^2 + 16\bar{h}^2(y)}\right]d\tau\,d\xi\right\}.$$

then

$$a(y)\,2\lambda(y)\,N_{10}\bar{\bar{A}}_z\gamma_1(\xi) = -C(y) - 2\lambda(y)\,\gamma_{222}(y)\,N_{10}\bar{\bar{A}}_z\gamma_{221} - -N_{1\lambda}\bar{A}_z\left[a(y)\sqrt{\frac{1+S}{1-S}} + \gamma_{22}\right];\quad g \in S_p. \tag{2.7}$$

For a wing in an infinite fluid both parts of equation (2.7) contain factors e^{ikx}. By multiplying equation (2.7) by e^{-ikx}, we eliminate the variable x [5, 8]. This also occurs in the general case, although the equation relative to e^{ikx} cannot be solved in explicit form, since it is possible to calculate the integrals in $N_{10}\bar{\bar{A}}_z\gamma$ in a closed form. In this connection let us introduce averaged equation (2.7) according to the following rule:

$$\bar{B} = \frac{\int\limits_{-1}^{+1} B\sqrt{\frac{1-x}{1+x}}\,dx}{\int\limits_{-1}^{+1} e^{ikx}\sqrt{\frac{1-x}{1+x}}\,dx}.$$

For $\overline{N_{10}\bar{\bar{A}}_z\gamma_1}$ and $\overline{\gamma_{222}(y)N_{10}\bar{\bar{A}}_z\gamma_{221}}$ we select representations in the form of

$$\overline{N_{10}\bar{\bar{A}}_z\gamma_1} = \frac{\bar{N}_1(k)}{\psi_1(k;\,\bar{h})\,2\pi}; \tag{2.8}$$

$$\overline{\gamma_{222}(y)\,N_{10}\bar{\bar{A}}_z\gamma_{221}} = \frac{\gamma_{222}(y)}{2\pi\psi_2(k;\,\bar{h})\,2\lambda(y)\,\lambda^{\circ}_{222}(y)}\left[\frac{ik}{\pi}\bar{N}_2(k)\,C(y) + C_2(y)\,\bar{N}_3(k)\right]. \tag{2.9}$$

When $\bar{h} \to \infty$ representations (2.8) and (2.9) are transformed into the expressions found in [9]. Functions $\bar{N}_i(k)$ are also obtained in [9].

Then,

$$a(y)\,2\lambda(y)\,\frac{\bar{N}_1(k)}{\psi_1(k;\,\bar{h})\,2\pi} + \frac{\gamma_{222}(y)}{2\pi\psi_2(\bar{k};\,\bar{h})\,\gamma^{0}_{222}(y)}\left[\frac{ik}{\pi}\bar{N}_2(k)\,C(y) + C_2(y)\,\bar{N}_3(k)\right] = -C(y) - N_{1\lambda}\bar{A}_z\left[a(y)\sqrt{\frac{1+S}{1-S}} + \gamma_{22}\right]. \tag{2.10}$$

With the introduction of a new variable $a_\lambda(y) = \int_{-1}^{+1}\left[a(y)\sqrt{\frac{1+S}{1-S}} + \right.$ $\left. + \gamma_{221}(y;\, S)\right] dy$ equation (2.8) is transformed into

$$a_\lambda(y) = \frac{\pi\psi_1(k;\, \bar{h})}{2\lambda(y)}\left\{a_* + \frac{\pi L a'_\lambda(\eta)}{N_1(k)}\right\}. \tag{2.11}$$

Here

$$a_* = -\frac{\pi\left\{C(y) + \frac{\gamma_{222}(y)}{\psi_2(k;\, \bar{h})\,\gamma^0_{222}(y)}\left[\frac{ik}{\pi}\bar{N}_2(k)\,C(y) + C_2(y)\,\bar{N}_2(k)\right]\right\}}{\bar{N}_1(k)} + \\ + \frac{\lambda(y)}{\psi_1(k)\,\pi}\,\gamma_{222}(y)\int_{-1}^{+1}\gamma_{221}(\xi)\,d\xi.$$

As follows from the solution to the plane problem of the nonstationary motion of a wing near a screen [7, 8], function $\gamma(S)$ can be written as:

$$\gamma(S) = \psi_c\, a_0(y)\sqrt{\frac{1+S}{1-S}} + \psi\gamma^0_1(S) + \psi_n\gamma^0_2(S).$$

Functions $\gamma^0_1(S)$, which correspond to the plane problem for an unlimited fluid, have been calculated in [9]. By using these results, we get

$$a_* = \frac{a_0(y)}{2} - \frac{\pi}{N_1(k)}\left[\frac{ik}{\pi}\bar{N}_2(k)\,C(y) + C_2(y)\,\bar{N}_2(k)\right]\left(\frac{\psi_n}{\psi_2} - 1\right) + ik\,C_2(y)\frac{\psi_n}{\psi_1}. \tag{2.12}$$

where La'_λ is the integral operator, whose core was obtained in monograph [4].

Now we must establish the connection between the functions which exclude ϕ_1 and ϕ_2 from (2.9). By definition when $\lambda \to \infty$

$$a_\lambda(y) = \pi\left[\frac{\psi_c a_0(y)}{2\lambda(y)} + \frac{\psi_n ik\, C_2(y)}{\lambda(y)}\right].$$

Constants $C_1(y)$ take the form of

$$C_2(y) = \frac{2}{\pi}\int_{-1}^{+1} \frac{F_1(x)}{\sqrt{1-x^2}}\,dx = \frac{2}{\pi}\int_{-1}^{+1} \frac{[F_1-(N_0-N_{01})\bar{A}_2\gamma_1]}{\sqrt{1-x^2}}\,dx,$$

$$C_3(y) = -\frac{1}{\pi}\int_{-1}^{+1} \sqrt{\frac{1-x}{1+x}}\,F_1(x)\,dx.$$

From equation (2.9) we find

$$a_\lambda(y) = \frac{\pi\psi_1(k)}{\lambda(y)}\,\alpha_9^1;$$

$$\alpha_9^1 = \underset{\lambda\to\infty}{\alpha_9} = \frac{a_0(y)}{2} + \frac{\psi_n}{\psi_c}\,ik\,C_2(y) -$$

$$-\frac{\pi}{\bar{N}_1(k)}\left[\frac{ik}{\pi}\,\bar{N}_2(k)\,C(y) + C_3(y)\,\bar{N}_3(k)\right]\left(\frac{\psi_n}{\psi_c}-1\right).$$

By comparing the two expressions for $a_\lambda(y)$, we get the relationship we need

$$\psi_n = \psi_2; \quad \psi_1 = \psi_c.$$

Now, combining the results of equation (2.9), we write the intego-differential equation for a wing of great aspect ratio near a screen in a nonstationary flow

$$a_\lambda(y) = \frac{\pi\psi_c}{\lambda(y)}\left[\alpha_9 - \frac{1}{2\pi\,|\bar{N}_1(k)|}\int_{-1}^{+1} a_\lambda'(\eta)\,K\,[k_\lambda(y-\eta)]\,d\eta,\right. \qquad (2.13)$$

where

$$\alpha_9 = \frac{a_0(y)}{2} + \frac{\psi_n}{\psi_c}\,ik\,C_2(y).$$

The core K (9) has the form of [4]

$$K(g) = \frac{N_{-1}P\,|y-\eta|}{(y-\eta)} + \frac{u-\eta}{(y-\eta)^2+16\bar{h}^2}\,N_{-1}\left(P\sqrt{(y-\eta)^2+16\bar{h}^2}\right) -$$

$$-\frac{4\bar{h}}{(y-\eta)^2+16\bar{h}^2}\,N_0\left(P\sqrt{(y-\eta)^2+16\bar{h}^2}\right).$$

Where $K \to 0$, $N_1(k) \to -1$ and from (2.11) we get the Prandtl equation for a wing near a screen in a stationary flow [4]. Here

$$K(y-\eta) = \frac{1}{(y-\eta)} + \operatorname{sign} F \frac{(y-\eta)}{(y-\eta)^2 + 16\bar{h}^2}.$$

Thus, the Prandtl problem for a wing in a nonstationary flow is reduced to two one-dimensional integral equations (2.5), (2.13), where equation (2.5) corresponds to the equation of the stationary theory.

This result, which is the direct result of breaking the general solution down into three components, is significant in that the authors of known theory [1, 2], by introducing integral equations of the "reduced circulation" type, have found one one-dimensional equation.

3. In determining aerodynamic coefficients C_y and C_x a good first approximation gives us the solutions introduced in [3, 4].

$$\Gamma(y) = \Phi \sqrt{1-\bar{y}^2}.$$

We use this representation for the approximate solution of (2.13). By assuming $a_\lambda(y) = \Phi\sqrt{1 - y^2}$ for constant Φ, we get

$$\Phi = \frac{\frac{\pi\psi_c\alpha_0}{\lambda(0)}}{1 + \frac{\pi\psi_c}{2\lambda(0)\,|\bar{N}_1(k)|}}\,\zeta k_\lambda, \tag{3.1}$$

where ζk_λ is obtained from a formula in [4]:

$$\zeta k_\lambda \doteq 1 - \frac{2}{\pi^2}\int_{-1}^{+1} \sqrt{1-y^2} \int_{-1}^{+1} \frac{\eta}{\sqrt{1-\eta^2}} \left\{K[k_\lambda(y-\eta)] - \frac{1}{(y-\eta)}\right\} d\eta. \tag{3.2}$$

and k_λ - is the Strouhal span number.

The coefficient of the lifting force of the wing is calculated by formula

$$C_y = \frac{\lambda}{\pi}\int_{-1}^{+1}\int_{-1}^{+1} \gamma(\xi, \eta)\, d\xi\, d\eta. \tag{3.3}$$

Now let us write the coefficient for the lifting force of a wing in the form of two components:

$$C_y = C_{y\text{в}} + C_{y\text{и}},$$

where $C_{y\text{в}}$ is the coefficient of the lifting force determined by vortex movements; $C_{y\text{и}}$ - the coefficient of the lifting force determined by the connected mass of the wing.

Now let us find components $C_{y\text{в}}$ and $C_{y\text{и}}$:

$$C_{y\text{в}} = -\frac{a_\infty \psi_c}{1 + \frac{a_\infty \psi_c}{\pi\lambda\,|\overline{N}_1(k)|}\xi_{k_\lambda}} \frac{C(k)}{\pi} \int_{-1}^{+1} \sqrt{\frac{1-x}{1+x}} F_{\text{э}}^{0}(x)\,dx + {}$$
$$+ 2\psi_n ik \int_{-1}^{+1} \sqrt{\frac{1-x}{1+x}} F_{\text{э}}(x)\,dx \left[1 - \frac{1}{1 + \frac{a_\infty \psi_c}{\pi\lambda\,|\overline{N}_1(k)|}\zeta_{k_\lambda}}\right] + {}$$
$$+ 2\dot{\psi} \int_{-1}^{+1} \frac{F_{\text{э}}(x)}{\sqrt{1-x^2}} x\,dx \left\{1 - \frac{\psi_c}{\psi\left[1 + \frac{a_\infty \psi_c}{\pi\lambda\,|\overline{N}_1(k)|}\zeta_{k_\lambda}\right]}\right\}; \quad (3.4)$$

$$C_{y\text{и}} = -\psi_n 2ik \int_{-1}^{+1} \sqrt{1-x^2} F_1(x)\,dx. \quad (3.5)$$

Here

$$F_{\text{э}}(x) = F_1(x) - [N_0 - N_{01}]\,\overline{A}_z \gamma_1,$$

and C(k) is the Theodorsen coefficient [2].

In calculations the theoretical value of $a_\infty = 2\pi$ (with the effect of the viscosity of the fluid considered) can be assumed to be $a_\infty \approx 5.45$.

For a stationary flow $C_{y\text{и}} = 0$, while

$$C_{y\text{э}} = -\frac{a_\infty \psi}{1 + \frac{a_\infty \psi}{\pi\lambda}} \int_{-1}^{+1} \sqrt{\frac{1-x}{1+x}} F_\text{э}(x)\,dx + $$

$$+ 2\psi \int_{-1}^{+1} \frac{F_\text{э}(x)}{\sqrt{1-x^2}} x\,dx \left[1 - \frac{1}{1 + \frac{a_\infty \psi}{\pi\lambda}\zeta}\right]. \qquad (3.6)$$

The first term in (3.6) gives us the well known value of the wing coefficient in a limited flow; the second term, which has an order of $1/\lambda$, represents the refinement which the present method introduces into the Prandtl theory. For a plane lifting surface the second term in (3.6) is equal to zero, and the results will be in complete agreement with the classical theory of the supporting line [3, 4].

Functions ϕ_c, ϕ_Π, ϕ were obtained in [7, 8, 11] for forward and reciprocal wing oscillations.

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